

## ACOT™ Stability Testing

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### Abstract

ACOT (Advanced Constant ON Time) Buck converters are non-linear hysteretic topology converters. Evaluating these converters using classical Bode Plot open loop gain-phase measurement may yield inaccurate results and can lead to incorrect conclusions. When checking the stability of ACOT converters, Richtek recommends step-load transient testing in time domain rather than open loop gain/phase measurements. This application note describes the background, measurement methods and acceptance criteria for proper stability testing of these converters. Included are explanations of the design and measurement tools, waveform analysis, examples and precautions when performing fast step-load measurements.

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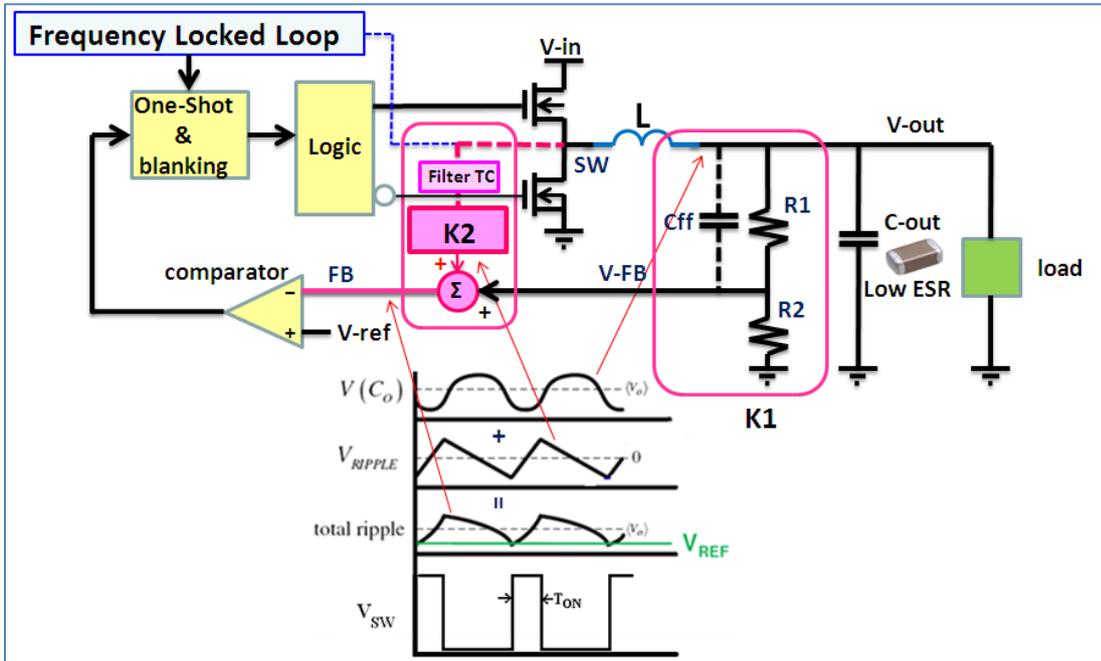
#### Release History:

August 2013: Preliminary release with design tool V1.0

September 2013: Release with design tool V1.1 (damping factor formula correction)

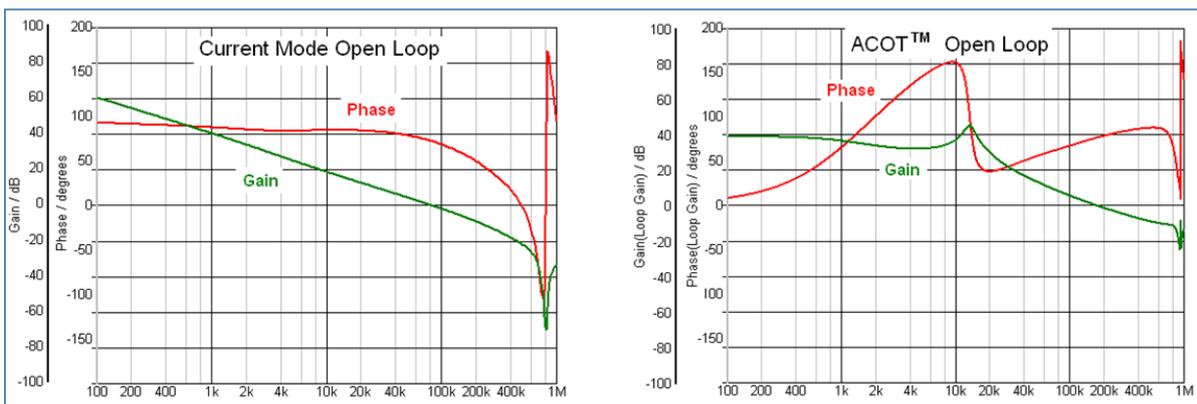
**1. INTRODUCTION**

ACOT Buck converters are non-linear hysteretic topology control systems. ACOT converters make use of an internally generated ripple signal, which is added to the ripple and the DC level from the converter output. These are summed and then compared with an internal reference. When this sum drops below the reference, the comparator triggers the ON time One-Shot generator. See figure 1.



**FIGURE 1: ACOT BUCK CONVERTER CONTROL MECHANISM AND OPERATION**

In an ACOT control system, the output feedback voltage does not provide a linearly changing signal like it does in current mode converters, but rather a dynamically changing modulation signal for the hysteretic control mechanism. As a result, conventional open loop phase margin analysis (performed by inserting a sweep signal between the output and the feedback network) interfere with the hysteretic control loop and yield results quite different than a standard current mode or voltage mode converter. Conclusions based on these conventional measurements may be incorrect. See examples in figure 2 below: Open Loop gain/phase of Current Mode system (left) vs. ACOT system (right).



**FIGURE 2: OPEN LOOP GAIN/PHASE SIMULATION OF CURRENT MODE AND ACOT CONVERTERS SHOW VERY DIFFERENT RESULTS**

However, ACOT converters may be mathematically analyzed in frequency domain by calculating their **closed loop response**: This is done by adding the sine-wave sweep signal to the **control input** (at Vref) and viewing the Bode plot of the output voltage versus control input as shown in figure 3.

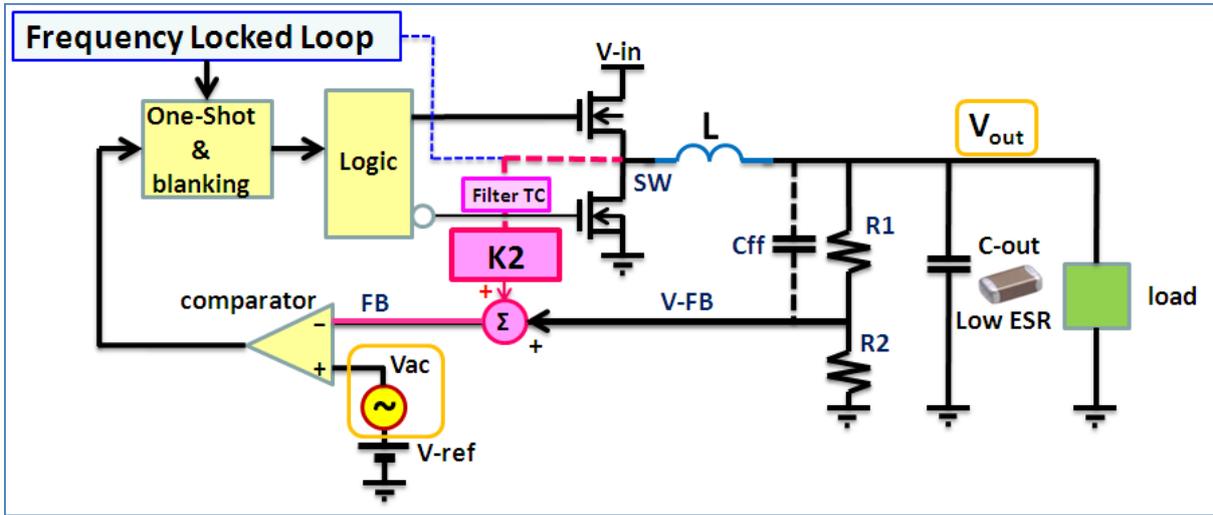


FIGURE 3: CLOSED LOOP MEASUREMENT OF ACOT BUCK CONVERTER

This method of calculating the closed loop response of ACOT provides accurate results, because the sweep insertion signal is added to a stable DC control signal and therefore does not interfere with the dynamically changing modulation signals. The results are very comparable to that of Current Mode converters, as shown in examples in figure 4: Closed Loop Gain/Phase of Current Mode (left) vs. ACOT (right).

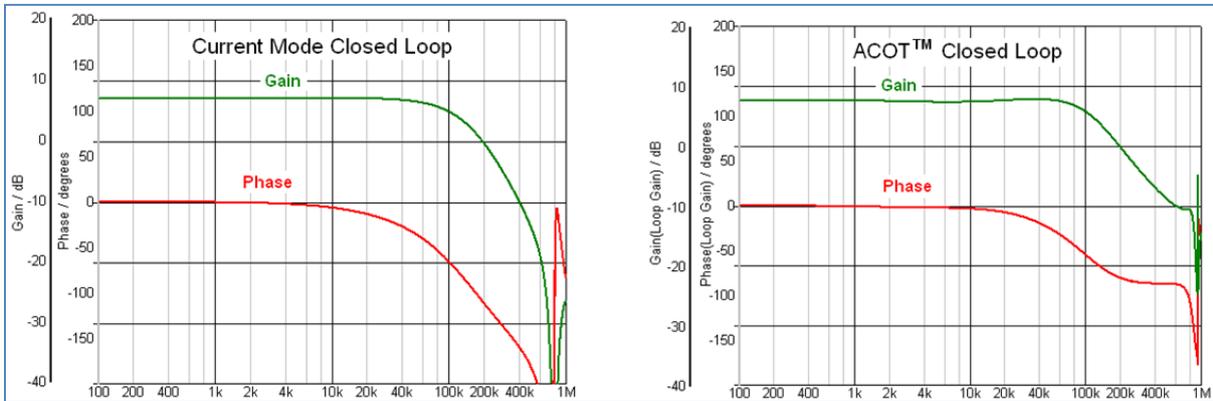
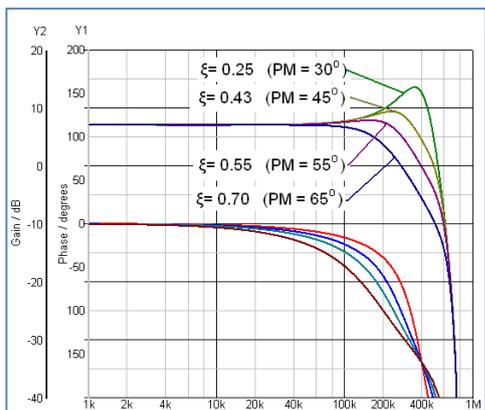


FIGURE 4: CLOSED LOOP GAIN/PHASE SIMULATION OF CURRENT MODE AND ACOT CONVERTERS SHOW SIMILAR GAIN AND PHASE CURVES



In closed loop mathematical analysis, the system stability can be found by observing the closed loop response. Flat gain response is considered stable (critically damped or over-damped response), while severe peaking in the gain with abruptly decreasing phase around resonance frequency (under-damped response) corresponds to low phase margin in the system open loop gain. See figure 5: Examples of Closed Loop gain/phase with various damping factors.

Very low damping factor  $\xi$  will correspond with low phase margin. To secure an open loop phase margin above  $45^\circ$ , the closed loop damping factor  $\xi$  should be  $> 0.43$ .

FIGURE 5: CLOSED LOOP GAIN-PHASE WITH VARIOUS DAMPING FACTORS (BASED ON 800KHZ CURRENT MODE BUCK CONVERTER)

## 2. ACOT BUCK CONVERTER STABILITY BOUNDARIES

Conventional Constant On Time (COT) Buck converters need a feedback signal that is in phase with the inductor current for stability. It is for this reason that conventional COT converters use output capacitors with some minimum ESR, because this ESR output ripple is in phase with the inductor current. When using very low ESR output capacitors, the ESR output ripple becomes too small to be useful and the remaining feedback signal has too much phase delay. The result is instability and oscillation.

ACOT converters overcome this limitation because they utilize an internal ripple generator which is in phase with inductor current and is added to the feedback signal. This permits the use of very low ESR output capacitors, and means that ACOT converters will be stable over a wide range of applications and operating conditions. However, there are some conditions that could result in unstable switching:

- a. When very small output capacitors ( $< 5\mu\text{F}$ ) are used, the larger (phase shifted) output ripple may cause sub harmonic instability because the output ripple amplitude is much bigger than internally generated ripple. In normal applications C-out ranges from  $22\mu\text{F} \sim 66\mu\text{F}$  so this is usually not a problem.
- b. In higher duty-cycle applications (higher output voltages or lower input voltage), the internal ripple signal will increase in amplitude. Before the ACOT converter can react to an output voltage fluctuation, the voltage change on the feedback signal must exceed the internal ripple amplitude. Because of the large internal ripple in this condition, the response may become too slow, and may show an under-damped response. This can cause some ringing in the output, and is especially visible at higher output voltage applications like 12V to 5V where duty-cycle is high and the feedback network attenuation is large, adding to the delay.

External components that influence this behavior:

- Higher feedback network attenuation (higher output voltage applications) will make it worse
- Larger output capacitance will make it worse because output fluctuations are also smaller and delayed
- Larger inductor values will make it worse because the energy the system can deliver in one  $T_{on}$  period is lowered

For these applications, adding a feed-forward capacitor ( $C_{ff}$ ) across the upper feedback resistor is recommended. This increases the damping of the control system.

See figure 6 below.

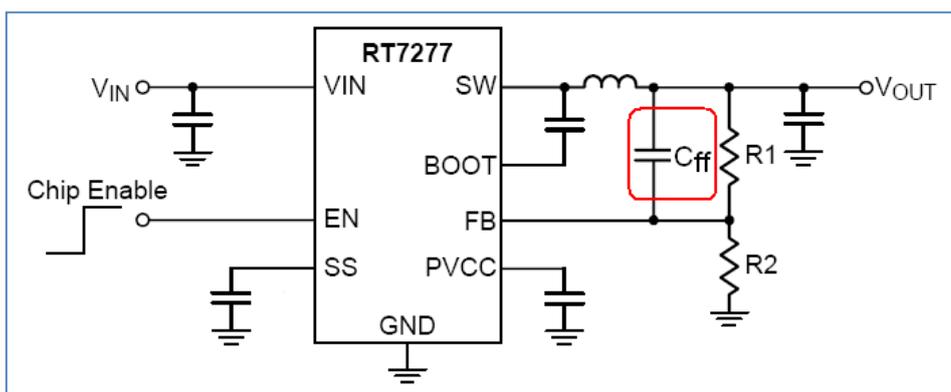


FIGURE 6: ACOT™ CONVERTER SCHEMATIC. FEED-FORWARD CAPACITOR  $C_{ff}$  CAN BE USED TO INCREASE SYSTEM DAMPING

The Recommended Application Components table in the ACOT device datasheet will show typical values for  $C_{ff}$  that will result in stable operation. For optimal stability and total application verification, Richtek has developed a [design tool](#) that can help determining the optimal value for  $C_{ff}$ .

### 3. ACOT STABILITY DESIGN TOOL

The ACOT stability design tool can be used to calculate the optimal value of the feed-forward capacitor  $C_{ff}$  for any ACOT Buck converter application. Please download the [ACOT stability design tool](#) from the Richtek website.

After entering the application parameters, (ACOT device, input & output voltage, output capacitance and ESR, inductor value), the tool will first calculate the feedback resistors, and then the control system closed loop response without feed-forward capacitor. It will then determine the optimal  $C_{ff}$  value for best system damping.

The user can select different feed-forward capacitor values and see the impact on closed loop response. The damping factor  $\xi$  will be calculated and can be used to judge the overall converter stability.

Revision:	1.1
Attention:	1. "Analysis ToolPak" Add-in is required. 2. Skyblue cells require user input 3. For use with Excel version 2007 or higher
<b>Operation Parameters of Power Stage</b>	
Richtek ACOT™ Partnumber:	RT7277
Input Voltage:	12 V
Output Voltage:	5 V
<b>Power Inductor Parameters</b>	
Inductance value:	4.7 $\mu$ H
<b>Output Capacitor Parameters</b>	
Number of Output Capacitors:	1
Capacitance of Each Individual Capacitor:	80 $\mu$ F
ESR of Each Individual Capacitor:	2 $m\Omega$

Figure 7: Circuit parameter fields. This example is a 5V application with 80 $\mu$ F of ceramic output capacitors.

For this application, the designer will need to add some feed-forward capacitance.

FIGURE 7

K1 Network Parameters	
Recommended Value	User-Selected Value
R2 22 $k\Omega$	R2 22 $k\Omega$
R1 121.791 $k\Omega$	R1 121 $k\Omega$
Use User-Selected Value (Y/N)? <input type="checkbox"/> YES	
Without Cff Value:	
f <sub>w</sub> 18.6209 $k$ Hz	
$\xi$ 0.20678	
Insufficient stability margin	
Cff 179.415 $\mu$ F	Cff 68 $\mu$ F
Use User-Selected Value (Y/N)? <input checked="" type="checkbox"/> YES	
With selected Cff Value:	
$\xi$ 0.50916	
Sufficient stability margin	

Figure 8: Calculation of the feedback network and damping factor  $\xi$  without and with  $C_{ff}$ . Optimal value for  $C_{ff}$  is 180pF, which will result in a damping factor > 0.707. When using  $C_{ff}$  = 68pF, the damping factor will be 0.509, which is slightly under-damped condition, but provides sufficient stability margin.

The tool will plot the gain&phase for both conditions.

FIGURE 8

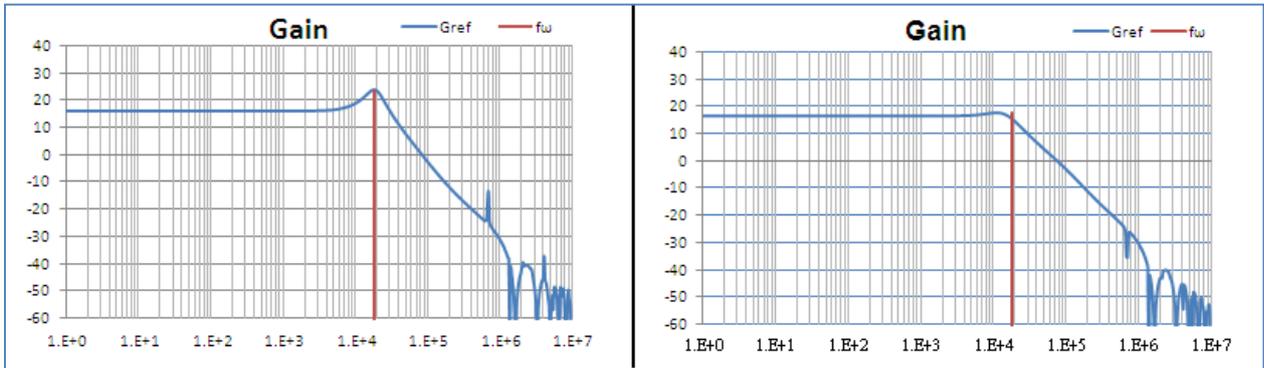


FIGURE 9: CLOSED LOOP GAIN WITHOUT  $C_{ff}$  (LEFT) AND WITH  $C_{ff}$  = 68PF (RIGHT)

## 4. ACOT BUCK CONVERTER STABILITY TESTING

Although ACOT converters can be mathematically analyzed by closed loop calculation, this method cannot be used for practical testing, because the converter control input ( $V_{ref}$ ) is not accessible from outside the IC. However because of the relation between frequency domain closed loop damping factor and time domain load transient characteristics, ACOT converter stability can be readily measured by applying fast load steps and observing the resulting output voltage fluctuation.

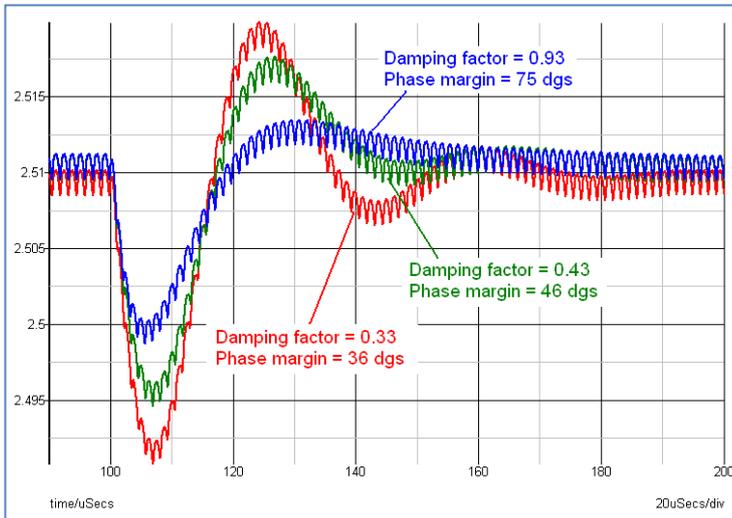


FIGURE 10: ACOT BUCK CONVERTER OUTPUT VOLTAGE DURING LOAD STEP

Figure 10 at the left shows a buck converter output voltage fluctuation during a fast load step transient with differing damping factors ( $\xi$ ).

It is apparent that the transient output voltage during a step-load will show different behavior based on the dampening factor used:

A system with sufficient damping (blue waveform) will not show any ringing, and the output voltage will smoothly move to its final value. This correlates with a very good phase margin, in this case  $\sim 75^\circ$ .

When the damping factor is lowered, ringing starts to appear in the transient response (green waveform) and the correlated phase margin is low but acceptable for

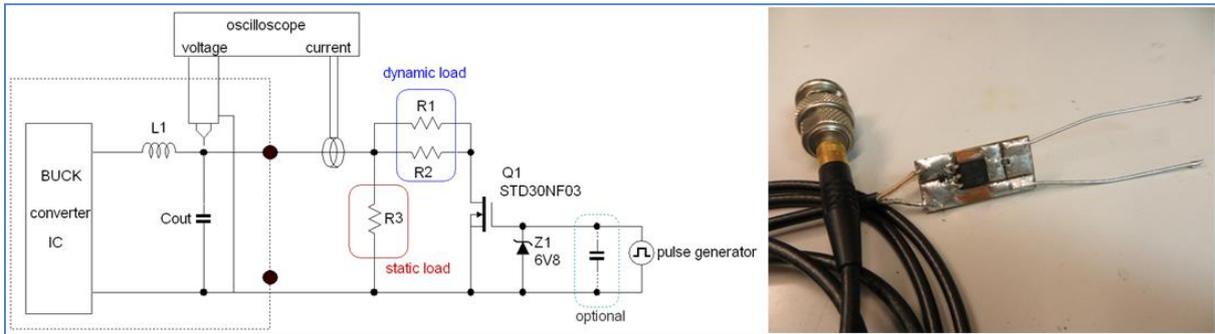
most applications at  $46^\circ$ . As the dampening factor is reduced further, ringing increases and phase margin erodes. (Red waveform)

For ACOT converters, damping factors of  $> 0.43$  are acceptable, and a damping factor  $> 0.50$  will guarantee stability including device tolerances. This means that output voltage may show some slight ringing, which quickly damps out in  $< 1.5$  cycles.

## 5. PRACTICAL MEASUREMENT SETUP

To check stability via a fast load transient, a load step with a speed that exceeds the converter bandwidth must be applied. For ACOT, loop bandwidth can be in the order of  $100 \sim 200\text{kHz}$ , so a load step with  $500\text{nsec}$  maximum rise time ( $di/dt \approx 2A/\mu\text{sec}$ ) ensures the excitation frequency is sufficient. ( $> 300\text{kHz}$ ). The actual amplitude of the load step is not critical, generally a current step of  $20 \sim 30\%$  of max load is recommended. So for a 3A converter, a 1A peak-peak current step with variable DC value is suitable. For converters with enhanced light load efficiency mode, it is important that the converter operates in PWM mode, outside the light load efficiency range, and below any current limit threshold. For these reasons, a load transient from  $1/3$  to  $2/3$  of maximum load is reasonable.

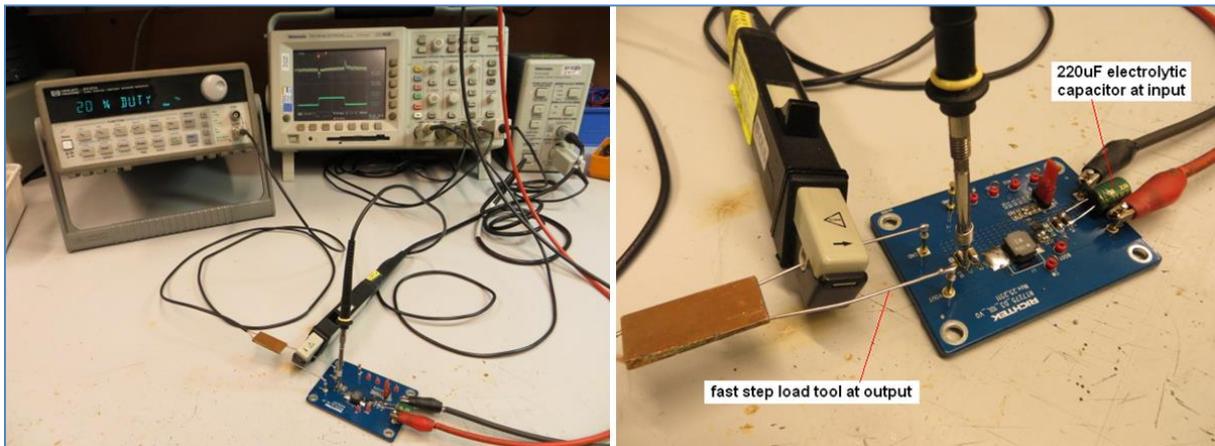
Most electronic loads cannot generate very fast load steps. For these cases a simple tool can be used to generate fast load steps. Figure 11 below shows an example of a tool that can be used to generate fast load steps: It consists of a MOSFET switch driven by a pulse generator. The MOSFET switches a resistor to the converter output. Another resistor is connected to the output directly to set the static load condition.



**FIGURE 11**

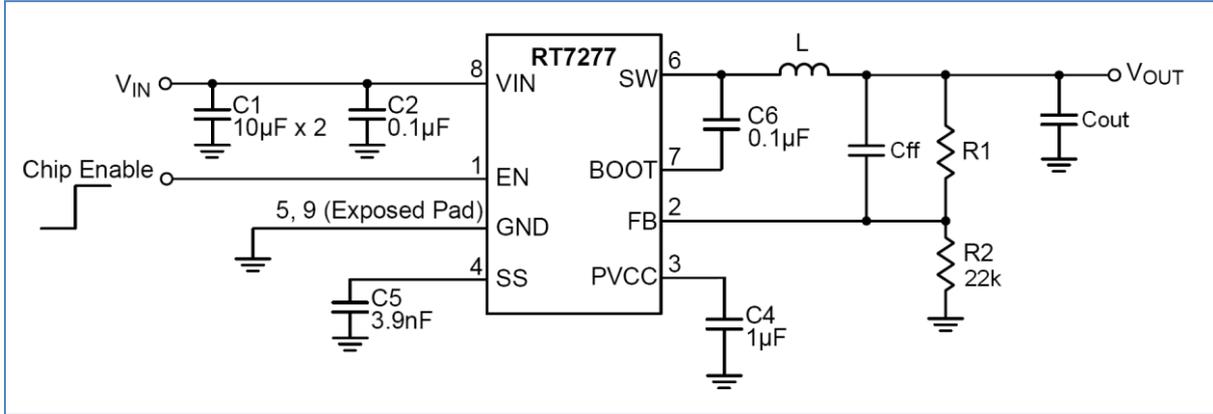
This tool can create very fast  $di/dt$ , (rise times of  $\sim 50\text{nsec}$ ) but these speeds can induce ringing which is not due to converter stability but due to Buck converter input ringing. (supply lines and ceramic input cap, PCB traces etc). Increasing the step-load rise times to  $\sim 500\text{nsec}$  will reduce this effect. The driving speed of the pulse generator determines the switching speed. To slow down speed, a capacitor can be added at the MOSFET gate to reduce the driving speed. As an extra precaution, a  $220\mu\text{F}$  electrolytic capacitor can be added in parallel with the Buck input capacitor close to the IC, to damp any ringing from input side. To avoid too high power dissipation in the dynamic load resistors, keep the pulse load duty factor low, around 20% or less.

Figure 12 shows the typical measurement setup.



**FIGURE 12**

Some examples of fast step response measurements are shown below:  
 (Based on RT7277GSP in 5V and 1.8V application)



<b>5V application:</b>			
12V→5V, Cout=60µF, L=4.7uH, C <sub>ff</sub> = 0pF	12V→5V, Cout=60µF, L=4.7uH, C <sub>ff</sub> = 39pF	12V→5V, Cout=60µF, L=4.7uH, C <sub>ff</sub> = 82pF	12V→5V, Cout=60µF, L=4.7uH, C <sub>ff</sub> = 150pF
$\xi = 0.24$ (from design tool) severe under-damped	$\xi = 0.44$ (from design tool) under-damped but OK	$\xi = 0.65$ (from design tool) sufficiently damped: OK	$\xi > 0.707$ (from design tool) (actual $\xi$ value ~ 1.1) Over-damped : Optimal stable

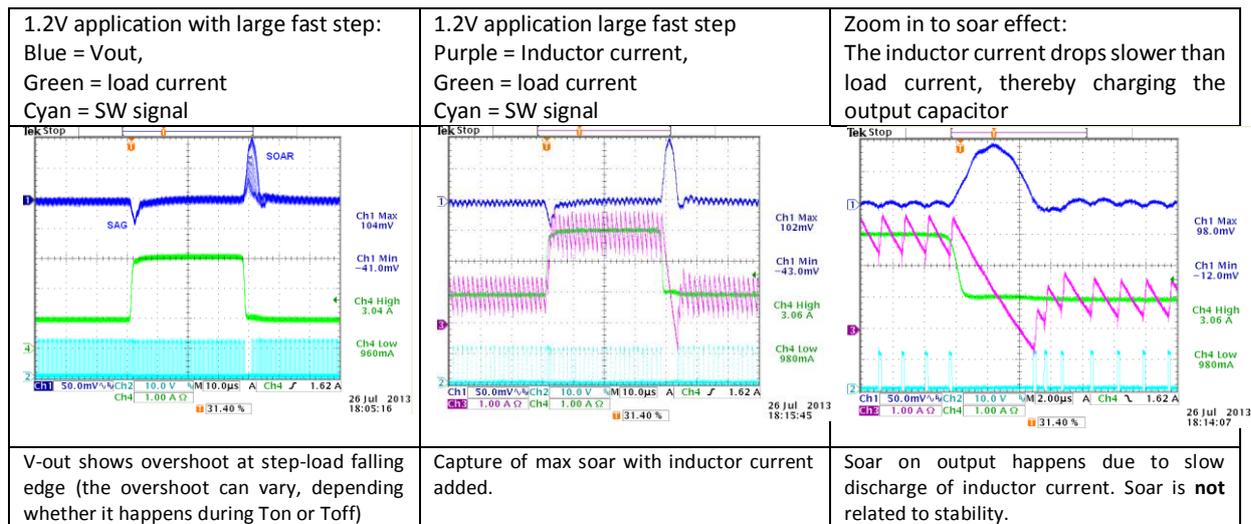
<b>1.8V application:</b>			
12V→1.8V, Cout=44µF, L=2.2uH, C <sub>ff</sub> = 0pF	12V→1.8V, Cout=44µF, L=2.2uH, C <sub>ff</sub> = 15pF	12V→1.8V, Cout=44µF, L=2.2uH, C <sub>ff</sub> = 100pF	12V→1.8V, Cout=4.7µF, L=2.2uH, C <sub>ff</sub> = 0pF
$\xi = 0.35$ (from design tool) under-damped	$\xi = 0.43$ (from design tool) under-damped but OK	$\xi = 0.64$ (from design tool) sufficiently damped: OK	$\xi = 0.11$ (from design tool) Cout too small: sub-harmonic oscillation. Increase Cout.

## 6. PRECAUTIONS WHEN MAKING VERY FAST LOAD STEP MEASUREMENTS

During step-load rising edge there will be an output voltage **sag** effect, where undershoot is mainly determined by the reaction speed of the converter and the max duty-cycle that the converter can achieve.

During fast load step falling edge there will be an output **soar** effect, where the output can show some overshoots because the inductor current cannot ramp down fast enough and charges the output capacitor.

Output soar is mainly determined by load step amplitude, inductor value and output capacitance, as the ACOT converter will temporarily go into 0% duty cycle mode. Soar effects are especially visible in low output voltage supplies, where inductor current  $di/dt$  is low due to  $V_o/L$  is low. These effects should not be mistaken for instability.



## 7. SUMMARY

ACOT converters incorporate an internal ripple generator which makes them suitable for use with very low ESR output capacitors. As result, ACOT converters will be stable over a wide range of applications and operating conditions. In some applications (especially higher output voltage applications), ACOT converters may show under-damped response. By adding a feed-forward capacitor, the system damping can be increased, to achieve a well damped response.

To determine the optimal value of the feed-forward capacitor, a design tool is available which can calculate the required feed-forward capacitor for any application. The design tool will also calculate the closed loop system damping factor, which can be used to judge the system stability.

For practical stability measurements, time domain measurements using fast load steps are recommended. In these step-load measurements, stability can be judged by observing the output voltage fluctuation during the load step. Well damped systems will show minimal ringing in the output voltage during fast load steps.

Applying traditional Open Loop phase margin measurements to ACOT Buck converters can show misleading results, because ACOT converters are non-linear hysteretic topology control systems, and the feedback signal from output is not a linearly changing signal like in current mode converters, but rather a dynamically changing modulation signal for the hysteretic control mechanism.

For this reason, traditional Open Loop phase margin measurements to analyze ACOT converter stability are not recommended, as conclusions based on these measurements may not be accurate.